LATERAL AND VERTICAL MOTIONS IN EUROPA'S ICE SHELL. F. Nimmo, *Dept. Earth and Space Sciences, University of California Los Angeles, (nimmo@ess.ucla.edu)*.

Characterizing the lateral and vertical motions that occur within Europa's ice shell is challenging but important. Vertical motions can transport nutrients and thus have astrobiological importance, while lateral movements can cause thinning of the ice shell. Future mission design will be affected by what we think we know about the characteristics of Europa's ice shell. Models and inferences of vertical and lateral motion will help us to constrain the ice shell thickness, and also to estimate the characteristic strain rates and stresses (ie. the shell dynamics).

LATERAL MOTION

Lateral extension is very obvious in bands [1], though minor amounts of strike-slip or compressive motion may also occur [2; 3]. The localized, high stretching factor rifting is very different to the diffuse, lower stretching factor extension seen on Ganymede. Localized extension is favoured by high strain rates and low shell thicknesses. Recent work by [4] suggests that an extensional strain rate $> 10^{-15}\ s^{-1}$ is required to form bands on Europa. The associated stresses are $\approx$0.3 MPa, similar to estimates inferred from flexural studies but several orders of magnitude larger than present day tidal stresses. The fact that bands appear to be elevated relative to their surroundings suggests either compositional or (recent) thermal buoyancy [5].

A less obvious but equally important kind of lateral motion is flow in the lowermost part of the shell. Lateral shell thickness contrasts, *even if isostatically compensated*, produce pressure gradients which drive flow. Thus, topography produced by lateral shell thickness contrasts decays with time [6]. The rate of decay can be very rapid, especially for thick shells. However, the rate of decay is slower for non-Newtonian materials, such as ice, than it is for Newtonian ones. Global shell thickness contrasts can probably be maintained for 50 Myr, but local ($\sim$100 km) variations cannot [7].

Strike slip motion has also been identified on Europa [3] and is almost certainly driven by a "tidal walking" process [8]. It has been proposed that shear-heating at such sites could lead to the formation of double ridges [9]. If shear heating leads to melting, this provides a potential source of near-surface liquid water. Finally, shear heating zones are a source of weakness, which may explain why many bands appear to initiate at double ridges.

Compressional motion is rare on Europa, though folds have been identified in one area [10]. The imbalance between extension and compression is a puzzle. It is possible that compression is being accommodated by diffuse shortening which leaves little geological evidence.

VERTICAL MOTION

The evidence for vertical motion is less clear than that for lateral movements. Features termed pits, spots and domes may be the surface expression of subsurface vertical motion [11], but there is a lack of agreement on this point [12]. Even more controversially, chaos terrains may be the result of either diapiric activity [13] or melt-through caused by hydrothermal plumes [14]. A second kind of vertical motion occurs due to surface, rather than subsurface loads.

Thermal convection suffers from two problems in explaining the surface features. Firstly, it is much harder to initiate convection in Newtonian than non-Newtonian materials [15]. Furthermore, for the likely grain sizes and strain rates, the deformation of ice is controlled by the *slower* of the two relevant mechanisms [16]. The overall result is that convection is unlikely to occur unless the shell thickness exceeds 50 km This is substantially larger than earlier estimates of the critical shell thickness [11; 17].

Secondly, the temperature contrast generated by strongly temperature-dependent convection is determined by the rheological properties of the ice, and is small ($\sim$10 K) [15]. This temperature contrast is probably too small to generate the observed dome amplitudes of several hundred metres [18; 19]. Although a tidal feedback mechanism has been proposed [20], it is not clear that the very long wavelength tidal deformation will couple efficiently with the much shorter wavelength diapiric features [W. Moore, pers. comm.].

Compositional convection is an alternative mechanism for diapir formation. [5] proposed that compositional density contrasts might arise through the preferential loss of brines from warm ice. In this scenario, warm ice near the base of the shell loses salts, is more buoyant than the colder ice overlying it, and becomes gravitationally unstable. This Rayleigh-Taylor instability will grow most rapidly at a characteristic wavelength, which will determine the size of the ascending diapirs [21]. For most systems, the characteristic wavelength is a few times the thickness of the layer above the instability. The rise time of the resulting diapir depends on its radius r, density contrast $\Delta\rho$ and the viscosity structure of the ice. For viscosity which increases exponentially upwards with a characteristic length-scale δ, the rise time τ is given by

$$\tau \approx \frac{\eta_0 \delta}{r^2 \Delta\rho g} \left(\exp(h/\delta) - 1\right) \tag{1}$$

where g is gravity, η_0 is the viscosity at the base of the shell and h is the shell thickness. For likely diapir radii ($\sim$5 km) and ice viscosities ($\sim 10^{14}\ Pa\ s$), the rise time is O(1 Myr). The nature of the return flow mechanism in the case of compositional convection is not clear, but may involve broad-scale downwards motion.

Vertical motions in response to surface loading also occur. The horizontal distance over which the deformation occurs provides information about the elastic thickness of the ice shell [22; 23]. Frequently, the margins of chaos terrain are a few hundred metres lower than the surrounding areas, and appear to have downdropped along sharp contacts [22]. This downdropping is consistent with scenarios in which the underlying ice is thinned (or even completely melted). While chaos terrain may be elevated with respect to the surroundings at the present day [13], this topography may post-date the original formation of the chaos.

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Summary and Future Questions

The availability of topographic data is now allowing us to place quantitative constraints on processes happening within Europa's ice shell. However, as yet neither the *spatial* nor the *temporal* variations in these processes have been properly addressed. Temporal variations are detectable with geological mapping; spatial variations are dependent on data availability. It is therefore critically important to maximize the amount of data available, which in practice will mean increasing reliance on photoclinometric methods [24].

The estimation of stresses and strain rates within Europa's ice shell is at an early stage. However, it is already clear that many of the features observed imply stresses far in excess of the present-day tidal stresses. Other sources of stress, such as those due to compositional or thermal buoyancy, must also be present. Again, whether there are temporal or spatial variations in stress or strain will be the subject of future investigations. Similarly, the reconciliation of global models of tidal dissipation with local geological features has barely begun.

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